On the Super Flavour Factory Target $\mathcal{L}_{\text{int}}$

or “SuperB with L>50/ab”


Tim Gershon (Warwick)

BNM2006 II
Translations

\[ \mathcal{L}_{\text{peak}} = 10^{34} / \text{cm}^2 / \text{s} \iff 1 / \text{fb/day} \iff 200 / \text{fb/year} \]

\[ \mathcal{L}_{\text{peak}} = 10^{35} / \text{cm}^2 / \text{s} \iff 10 / \text{fb/day} \iff 2 / \text{ab/year} \]

\[ \mathcal{L}_{\text{peak}} = 10^{36} / \text{cm}^2 / \text{s} \iff 100 / \text{fb/day} \iff 20 / \text{ab/year} \]

\[ \mathcal{L}_{\text{peak}} = 10^{37} / \text{cm}^2 / \text{s} \iff 1 / \text{ab/day} \iff 200 / \text{ab/year} \]

NB. 1000/ab = 1/zb

Assumes that:
- operating stability
- data taking efficiency
- useability of data
all remain similar to now
Shown in talk of M.Yamauchi (given by Y.Sakai), CKM2006, Nagoya, Dec. 15th 2006

Talking about $10^{37}/\text{cm}^2/\text{s}$ might not be completely crazy?
Main physics channels

- Precision CKM metrology
- Search for inconsistent CPV phenomena in (eg.) $b \to sss$
- New FCNCs
- Search for right-handed currents in (eg.) $b \to s \gamma$
- Inconsistent flavour-mixing ($\Delta m$, $\Delta \Gamma$, "$\epsilon$") in $B_d$ or $D^0$
- Enhanced v. rare decays, (eg.) $b \to s \nu \nu$, $B_d \to \mu \mu$
- Direct CP violation in charm
- $\tau$ lepton flavour violation &/or CP violation
- ...
Operating Energy

- I will stick to the physics at the $\Upsilon(4S)$
- Clearly, much interesting physics at other centre-of-mass energies
- Higher luminosities will help!
• $\beta \equiv \phi_1 (b \to ccs)$
• $J/\psi K^0$
  • systematics limited by $\sim 2/ab$ (Yu.Nakahama @ CKM2006)
  • theory error $<<$ limiting experimental systematics
  • LHCb can do it anyway
• $J/\psi K^{*0}$
  • Belle [PRL 95 (2005) 091601] $N(BB)=275M$
  • $\sin(2\phi_1) = 0.24 \pm 0.31 \pm 0.05$ \hspace{1cm} $\cos(2\phi_1) = 0.56 \pm 0.79 \pm 0.11$
  • $\sigma[\cos(2\phi_1)]_{\text{stat}} \sim 0.06$ with $50/ab$; systematics???
• $D^{(*)}D^{(*)}K^0$
  • hard to quantity theoretical errors
CKM Metrology

- $\beta \equiv \phi_1 (b \rightarrow cud)$

- $Dh^0$
  - $\sigma[\sin(2\phi_1)]_{\text{stat}} \sim 0.04$, $\sigma[\cos(2\phi_1)]_{\text{stat}} \sim 0.05$ with $50/ab$; systematics???
  - $D_{CP}h^0$ will help for $\sigma[\sin(2\phi_1)]_{\text{stat}}$

- need to control model error (same problem as for $\gamma \equiv \phi_3$)
- theory error $\ll$ limiting experimental systematics
- LHCb could do $D_{CP}\pi^+\pi^-$ (challenging)

| Experiment | $\sin(2\beta) = \sin(2\phi_1)$ | $\cos(2\beta) = \cos(2\phi_1)$ | $|\lambda|$ | Correlations | Reference |
|------------|-------------------------------|-------------------------------|-------------|--------------|-----------|
| BaBar      | 0.45 $\pm$ 0.36 $\pm$ 0.05 $\pm$ 0.07 | 0.54 $\pm$ 0.54 $\pm$ 0.08 $\pm$ 0.18 | 0.975 $^{+0.093}_{-0.085}$ $^{+0.012}_{-0.002}$ | - | hep-ex/0607105 |
| Belle      | 0.78 $\pm$ 0.44 $\pm$ 0.22 | 1.87 $^{+0.40}_{-0.53}$ $^{+0.22}_{-0.32}$ | - | 0.07 stat between $\sin(2\beta)$ & $\cos(2\beta)$ | PRL 97, 081801 (2006) |
| Average    | 0.57 $\pm$ 0.30 $\chi^2$ = 0.3/1 dof (CL=0.59 $\Rightarrow$ 0.5$\sigma$) | 1.16 $\pm$ 0.42 $\chi^2$ = 2.5/1 dof (CL=0.12 $\Rightarrow$ 1.6$\sigma$) | - | uncorrelated averages | HFAG |
CKM Metrology

• $\alpha \equiv \varphi_2$
  • $\pi\pi, \rho\rho$ (Gronau-London; isospin)
  • theory error few degrees
  • requires modes with multiple $\pi^0$s – LHCb not competitive
  • $\pi\pi\pi (\rho\pi)$ (Snyder-Quinn)
    • isospin only used for neutral penguin – smaller theory error
    • only one $\pi^0$ – LHCb can do it (challenging)
  • $a_1\pi$ & others
    • errors associated to SU(3) may be small when $|P/T|$ is small
      (see, eg. J.Zupan @ CKM2006)
    • all charged tracks in the final state – potentially good for LHCb
CKM Metrology

• $\gamma \equiv \varphi_3$
  • DK (Gronau-London-Wyler; Atwood-Dunietz-Soni; others ...)
  • theory error completely negligible
  • most channels with one or less neutrals – good for LHCb
    (see M.Patel @ CKM2006)

• LHCb can also do $B_s^{\rightarrow}D_s K$ (SFF cannot)

<table>
<thead>
<tr>
<th>B mode</th>
<th>D mode</th>
<th>$\sigma(\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+\rightarrow DK^+$</td>
<td>$K \pi$</td>
<td>5° - 15°</td>
</tr>
<tr>
<td>$B^+\rightarrow D*K^+$</td>
<td>$K_s \pi \pi$</td>
<td>Under study</td>
</tr>
<tr>
<td>$B^+\rightarrow DK^+$</td>
<td>$K \pi \pi$</td>
<td>8°</td>
</tr>
<tr>
<td>$B^+\rightarrow DK^+$</td>
<td>$K_s \pi \pi$</td>
<td>15°</td>
</tr>
<tr>
<td>$B^0\rightarrow DK^{*0}$</td>
<td>$K \pi + KK + \pi \pi$</td>
<td>7° - 10°</td>
</tr>
<tr>
<td>$B^0\rightarrow DK^{*0}$</td>
<td>$K \pi \pi$</td>
<td>Under study</td>
</tr>
<tr>
<td>$B_s^{\rightarrow}D_s K$</td>
<td>$KK \pi$</td>
<td>5° - 15°</td>
</tr>
</tbody>
</table>

LHCb: DK channels combined sensitivity ~ 5° from 2/fb (1 nominal year)
• $|V_{ub}|$
  • already theory dominated
  • do not expect any significant contribution from LHCb
  • more data from SFF will help, but improvements will be slow and hard

**B \to \pi l\nu** Form Factor and $|V_{ub}|$

T. Onogi, CKM2006
**WG2 Summary talk**
Precision measurements of the UT undoubtedly extremely important

LHCb can do the angles

Improvement in $|V_{ub}|$ limited by theoretical uncertainties

SFF can contribute and make improvements in all measurements

not enough to motivate a major upgrade

Does not tell us what luminosity to aim for!
Warning:
can only be used as a guideline

Guesstimates based on
- 10/fb LHCb
- 50/ab Super B Factory

COMPLEMENTARITY

LHCb good for
- Bs decays & oscillations
- All charged track final states

Super Flavour Factory best for
- Inclusive measurements
- Modes with neutrals
  \( (\pi^0, K_S, \text{neutrinos, etc.}) \)
Key Measurements (Physics Case for SBF in 1 Slide)

**CP Violation in Hadronic $b\rightarrow s$**

\[ \sin(2\beta^{\text{eff}}) = \sin(2\phi_1^{\text{eff}}) \]

**Lepton Flavour Violation in $\tau$ Decay**

$B \rightarrow \tau \nu$

**Rates & Asymmetries in $b\rightarrow s\gamma$**

- $b \rightarrow u, c, t$
- $s \rightarrow u, c, t$
- $W^\pm$
- $v_{\nu_\tau}$
- $H^{\pm}$
Hadronic $b \to s$ Penguins

- Cleanest modes are $\varphi K^0$, $\eta' K^0$ & $K_S K_S K^0$
- theory errors ~ few degrees

<table>
<thead>
<tr>
<th>Mode</th>
<th>Experiment</th>
<th>$\sin(2\beta_{\text{eff}}) \equiv \sin(2\varphi_{\text{eff}})$</th>
<th>$C_{\text{CP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varphi K^0$</td>
<td><strong>BaBar</strong> N(BB)=384M</td>
<td>$0.12 \pm 0.31 \pm 0.10$</td>
<td>$0.18 \pm 0.20 \pm 0.10$</td>
</tr>
<tr>
<td></td>
<td><strong>Belle</strong> N(BB)=535M</td>
<td>$0.50 \pm 0.21 \pm 0.06$</td>
<td>$-0.07 \pm 0.15 \pm 0.05$</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td>$0.39 \pm 0.18$</td>
<td>$0.01 \pm 0.13$</td>
</tr>
<tr>
<td></td>
<td>Figures:</td>
<td>$\text{eps.gz png}$</td>
<td>$\text{eps.gz png}$</td>
</tr>
<tr>
<td>$\eta K^0$</td>
<td><strong>BaBar</strong> N(BB)=384M</td>
<td>$0.58 \pm 0.10 \pm 0.03$</td>
<td>$-0.16 \pm 0.07 \pm 0.03$</td>
</tr>
<tr>
<td></td>
<td><strong>Belle</strong> N(BB)=535M</td>
<td>$0.64 \pm 0.10 \pm 0.04$</td>
<td>$0.01 \pm 0.07 \pm 0.05$</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td>$0.61 \pm 0.07$</td>
<td>$-0.09 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td>Figures:</td>
<td>$\text{eps.gz png}$</td>
<td>$\text{eps.gz png}$</td>
</tr>
<tr>
<td>$K_S K_S K^0$</td>
<td><strong>BaBar</strong> N(BB)=347M</td>
<td>$0.66 \pm 0.26 \pm 0.08$</td>
<td>$-0.14 \pm 0.22 \pm 0.05$</td>
</tr>
<tr>
<td></td>
<td><strong>Belle</strong> N(BB)=535M</td>
<td>$0.30 \pm 0.32 \pm 0.08$</td>
<td>$-0.31 \pm 0.20 \pm 0.07$</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td>$0.51 \pm 0.21$</td>
<td>$-0.23 \pm 0.15$</td>
</tr>
<tr>
<td></td>
<td>Figures:</td>
<td>$\text{eps.gz png}$</td>
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</tr>
</tbody>
</table>
Hadronic $b \rightarrow s$ Penguins

- Naïve scaling of current experimental errors
  - $N(BB)$ required to reach theory error:
    - $\sim 10^{10}$ for $\eta'K^0$
    - $\sim 5 \times 10^{10}$ for $\phi K^0$
    - $\sim 5 \times 10^{10}$ for $K^0 S K^0$
  - Beyond naïve scaling?
    - time-dependent Dalitz plot analysis of $K^+KK^0$ (BaBar; hep-ex/0607112)
    - larger $f^0_0K^0$ contribution under $\phi K^0 \Rightarrow$ error on $S$ increases
- Improvements in theory uncertainties?
  - likely to be data driven
  - eg. SU(3) relations, understanding $\eta'$ form factor ($B \rightarrow \eta' l \nu$)
  - unlikely to go below 1% level

50/ab needed
Radiative $b \rightarrow s$ Penguins

• Key to NP sensitivity: measure the photon polarization
  
  Many approaches proposed
  • time-dependent asymmetry in $K^* \gamma$, $K_s \pi^0 \gamma$, etc.
  • interferences between resonances in $K\pi\pi\gamma$
  • conversions in $K^* \gamma \rightarrow K^* e^+e^-$
  • study of radiative $\Lambda_b$ decays
  • angular distributions in $K\phi\gamma$, etc.

only approach attempted to date!

see talk of A. Soni in this workshop
# Radiative $b \to s$ Penguins

<table>
<thead>
<tr>
<th>Mode</th>
<th>Experiment</th>
<th>$S_{CP}$ ($b \to s \gamma$)</th>
<th>$C_{CP}$ ($b \to s \gamma$)</th>
<th>Correlation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{*(892)}\gamma$</td>
<td><strong>BaBar</strong></td>
<td>$-0.21 \pm 0.40 \pm 0.05$</td>
<td>$-0.40 \pm 0.23 \pm 0.04$</td>
<td>0.07 (stat)</td>
<td>PRD 72 (2005) 051103</td>
</tr>
<tr>
<td></td>
<td><strong>Belle</strong></td>
<td>$-0.32^{+0.36}_{-0.33 \pm 0.05}$</td>
<td>$0.20 \pm 0.24 \pm 0.05$</td>
<td>0.08 (stat)</td>
<td><em>hep-ex/0608017</em></td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>$-0.28 \pm 0.26$</td>
<td>$-0.11 \pm 0.17$</td>
<td>0.07</td>
<td>HFA correlated average $\chi^2 = 3.2/2$ dof (CL=0.20 $\Rightarrow$ 1.3$\sigma$)</td>
</tr>
<tr>
<td>$K_{S\pi}^0\gamma$ (incl. $K^{*}\gamma$)</td>
<td><strong>BaBar</strong></td>
<td>$-0.06 \pm 0.37$</td>
<td>$-0.48 \pm 0.22$</td>
<td>0.05 (stat)</td>
<td>PRD 72 (2005) 051103</td>
</tr>
<tr>
<td></td>
<td><strong>Belle</strong></td>
<td>$-0.10 \pm 0.31 \pm 0.07$</td>
<td>$0.20 \pm 0.20 \pm 0.06$</td>
<td>0.08 (stat)</td>
<td><em>hep-ex/0608017</em></td>
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<tr>
<td></td>
<td>Average</td>
<td>$-0.09 \pm 0.24$</td>
<td>$-0.12 \pm 0.15$</td>
<td>0.06</td>
<td>HFA correlated average $\chi^2 = 5.1/2$ dof (CL=0.08 $\Rightarrow$ 1.8$\sigma$)</td>
</tr>
</tbody>
</table>

**Figures:**

![eps.gz png](image1.png)

![eps.gz png](image2.png)

![eps.gz png](image3.png)
Radiative $b \rightarrow s$ Penguins

- Naïve scaling of current experimental errors
  - Assuming theory uncertainties of few % due to higher order corrections
    see talk of A.Soni in this workshop
  - $N(BB)$ required to reach theory error:
    - $\sim 5 \times 10^{10}$ for $K_s \pi^0 \gamma$
  - only mode for which measurements currently exist

- Improvements in theory uncertainties?
  - in this case there is a **data driven** method to reduce the error
    $\Rightarrow$ study dependence of polarization on hadronic final state
    - eg. $S(K_s \pi^0 \gamma)$ vs. $m(K_s \pi^0)$, $S(K_s \pi^0 \gamma)$ with $S(K_s \eta \gamma)$, etc.
    $\Rightarrow$ much larger data samples necessary
Radiative $b \rightarrow s$ Penguins

- Observables sensitive to new physics fall into two categories:
  
  - (CKM favoured) $\times$ (helicity suppressed)
    - eg. $S(B_d \rightarrow K_s \pi^0 \gamma) \sim \sin(2\beta) \times \left(\frac{2m_s}{m_b}\right) \sim \sin(2\phi_1) \times \left(\frac{2m_s}{m_b}\right)$
    - SM uncertainty few %
    - requires new RH current but **does not require new CP phase**
  
  - (CKM suppressed) $\times$ (helicity suppressed)
    - eg. $S(B_s \rightarrow \phi \gamma) \sim \sin(\phi_s) \times \left(\frac{2m_s}{m_b}\right)$
    - tiny SM uncertainty (extremely clean null test)
    - requires **new RH current and new CP phase**
Radiative $b \to s$ Penguins

- Observables sensitive to new physics fall into two categories:
  - (CKM favoured) $\times$ (helicity suppressed)
    - e.g. $S(B_d \to K_s \pi^0 \gamma) \sim \sin(2\beta) \times (2m_s/m_b) \sim \sin(2\phi_1) \times (2m_s/m_b)$
    - SM uncertainty few %
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  - (CKM suppressed) $\times$ (helicity suppressed)
    - e.g. $S(B_s \to \phi \gamma) \sim \sin(\phi_s) \times (2m_s/m_b)$
    - tiny SM uncertainty (extremely clean null test)
    - requires new RH current and new CP phase

Essential to reduce the SM error
Can be done with data
Requires > 50/ab
A Word on $b \to d$ Penguins

To get required $N(B\bar{B})$ for $b \to d$ penguins:

1) Take $b \to s$ number and scale: $N(B\bar{B})[b \to s] / \left| V_{td} / V_{ts} \right|^2$

2) Scale from existing measurements, eg. $\sigma[S(K_s K_s)]_{stat} \sim 0.07 @ 50/ab$

3) Guesstimate based on measurements, $\sigma[S(\rho\gamma)]_{stat} \sim 0.07 @ 50/ab$

Theory uncertainties due to $c$- and $u$- penguin contributions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$S_{CP} (K_s K_s)$</th>
<th>$C_{CP} (K_s K_s)$</th>
<th>Correlation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$-1.28^{+0.80}<em>{-0.73}^{+0.11}</em>{-0.16}$</td>
<td>$-0.40 \pm 0.41 \pm 0.06$</td>
<td>$-0.32$</td>
<td>hep-ex/0608036</td>
</tr>
<tr>
<td>N(BB)=350m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>224</td>
<td>$\rho^0 \gamma$</td>
<td>$&lt; 0.4$</td>
<td>$0.77^{+0.21}_{-0.19} \pm 0.07$</td>
<td>$1.25^{+0.37+0.07}_{-0.33-0.06}$</td>
</tr>
<tr>
<td>226</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~40 events in 350M BB
~20 events in 380M BB
~100 events/ab $\Rightarrow$ 5000 events in 50/ab
More Penguins

• $b\rightarrow sll$ also very important probe of new physics
  • eg. forward-backward asymmetry in $B\rightarrow K^{*}l^{+}l^{-}$
  • ... but this is a very good channel for LHCb

• LHCb cannot do fully inclusive modes: $X_{s}l^{+}l^{-}$, $X_{s}\gamma$ also $X_{s+d}\gamma$, etc.
  • theoretically cleaner
  • requires full reconstruction
  • much larger data samples, typically > 100/ab

see also talk by M.Nakao

• Can also study inclusive hadronic final states
Lepton Flavour Violation

- Importance recently emphasised by many people
- No SM background \( \Leftrightarrow \mathcal{L}_{\text{int}} \) as high as possible

SFF sensitivity @ 10ab\(^{-1}\)
Leptonic Decays

- Assume $B \to \tau \nu$ will hit limits by 50/ab
  - $|V_{ub}|$
  - $f_B$ (lattice)
  - experimental systematics
    see talk by T. Iijima
- $B \to \mu \nu$ & $B \to e \nu$ require more data
- Some uncertainties can be reduced or removed using ratios
- $B \to D(*) \tau \nu$ provides additional observables and requires larger $L_{\text{int}}$
- $B \to \mu \mu$ & $B \to e e$ will be done by LHCb
  $B \to \tau \tau$ only at SFF, requires huge $L_{\text{int}}$
Summary

- Of the main channels that motivate a Super Flavour Factory
  - CPV in hadronic $b \rightarrow s$ penguins hits theory limit at about 50/ab
  - almost everything else will not be limited

**better to aim for a rounder number?**

- Of the interesting channels
  - most **do not** require time-dependent analysis
  - many require full reconstruction

⇒ **smaller energy asymmetry** (but with good vertexing)
⇒ **hermetic detector**
The FCNC Matrix

**FLAVOUR COUPLING:**

- $b \rightarrow s \ (\sim \lambda^2)$
  - $\Delta M_{B_s}$
  - $A_{CP}(B_s \rightarrow \psi \phi)$

- $b \rightarrow d \ (\sim \lambda^3)$
  - $\Delta M_{B_d}$
  - $A_{CP}(B_d \rightarrow \psi K)$

- $s \rightarrow d \ (\sim \lambda^5)$
  - $\Delta M_K$, $\varepsilon_K$

**ELECTROWEAK STRUCTURE**

<table>
<thead>
<tr>
<th>Structure</th>
<th>$\Delta F=2$ box</th>
<th>$\Delta F=1$ 4-quark box</th>
<th>$\gamma$ penguin</th>
<th>$Z^0$ penguin</th>
<th>$H^0$ penguin</th>
</tr>
</thead>
<tbody>
<tr>
<td>th. error $\leq 10%$</td>
<td></td>
<td>B$_d \rightarrow \phi K$</td>
<td>B$_d \rightarrow K \pi$, ...</td>
<td>B$_d \rightarrow X_s \gamma$, B$_d \rightarrow K \pi$, ...</td>
<td>B$_s \rightarrow \mu \mu$</td>
</tr>
<tr>
<td>exp. error $\leq 10%$</td>
<td></td>
<td>B$_d \rightarrow K \pi$, ...</td>
<td>B$_d \rightarrow X_d \gamma$, B$_d \rightarrow \pi \pi$, ...</td>
<td>B$_d \rightarrow \pi \pi$, ...</td>
<td>B$_d \rightarrow \mu \mu$</td>
</tr>
<tr>
<td>exp. error $\sim 30%$</td>
<td></td>
<td></td>
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</tbody>
</table>

**BEAUTY2003 panel discussion**

From G. Isidori, via O. Schneider

**kaon physics**